

Studying top quark decay into the polarized W-boson in the TC2 model

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We study the decay mode of top quark decaying into Wb in the TC2 model where the top quark is distinguished from other fermions by participating in a strong interaction. We find that the TC2 correction to the decay width $\Gamma(t \rightarrow bW)$ is generally several percent and maximum value can reach 8% for the currently allowed parameters. The magnitude of such correction is comparable with QCD correction and larger than that of minimal supersymmetric model. Such correction might be observable in the future colliders. We also study the TC2 correction to the branching ratio of top quark decay into the polarized W bosons and find the correction is below 1%. After considering the TC2 correction, we find that our theoretical predictions about the decay branching ratio are also consistent with the experimental data.

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I. INTRODUCTION

While the light quarks and leptons can be regarded as perturbative spectators to the electroweak symmetry breaking (EWSB), the massive top quark with a mass of EWSB scale suggests that top quark is potentially enjoying a more intimate role in the flavor dynamics and/or horizontal symmetry breaking. A potential implication of this is the possibility that there exist extra interactions for top quark, which distinguishes top quark from other fermions of the standard model (SM) at the electroweak scale. If this is true, the top quark physics will be much richer than that of the SM and possible large deviations of top quark properties from the SM predictions are expected [1]. Detailed study about such new physics effects may reveal useful information about the underlying interactions and the mechanism of EWSB. Such study is essential when one considers the advancement in experiments where the forthcoming CERN Large Hadron Collider (LHC) and the planned Next-generation Linear Collider (NLC) will serve as top quark factories and thus make the precise measurements of top quark properties possible [2]. In this paper, we restrict our discussion in the framework of the topcolor-assisted technicolor model (TC2) [3–5]. In this model, the third generation is singled out to participate in a special interaction called topcolor interaction. Such an interaction will cause the top quark condensation which can partially contribute to EWSB and also provide main part of top quark mass. The TC2 model generally predicts a number of scalars, and some of them couple very strongly to the top quark. So, we expect the TC2 corrections to the top quark properties are larger than those of the other models which treat generations in an egalitarian manner, such as the popular minimal supersymmetry model (MSSM) [6].

Although the various exotic production processes [7–10] and the rare decay modes of the top quark [11] can serve as a robust probe of the TC2 model, the role of the dominant decay mode $t \rightarrow Wb$ should not be underestimated [12]. One advantage of this decay mode is that it is free of non-perturbative theoretical uncertainties [13] and future precision experimental data can be compared with the accurate theoretical predictions. The other advantage of this channel is that the W-boson, as a decay product, is strongly polarized and the helicity contents (transverse-plus W_+ , transverse-minus W_- and longitudinal W_L) of the W-boson can be probed through the measurement of the shape of the lepton spectrum in the W-boson decay [14]. Among the three polarizations of the W-boson in the top quark decaying, the longitudinal mode is of particular interesting since it is useful to understand the mechanism of EWSB [15]. Therefore, the study of top quark decaying into the polarized W-boson can provide some additional information about both the tWb coupling and EWSB. On the experimental side, the CDF collaboration has already performed the measurement of the helicity component of the W-boson in the top quark decaying from Run 1 data and obtained the results

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$$\begin{aligned}\Gamma_L/\Gamma &= 0.91 \pm 0.37(stat.) \pm 0.13(syst.), \\ \Gamma_+/\Gamma &= 0.11 \pm 0.15 ,\end{aligned}$$

where Γ is the total decay rate of $t \rightarrow Wb$, and Γ_L and Γ_+ denote respectively the rates of top quark decaying into a longitudinal and transverse-plus W -boson. Although the error of these measurements is quite large at the present time, it is expected to be reduced significantly during Run 2 of the Tevatron and may reach 1% \sim 2% at the LHC [16]. On the theoretical side, the predictions of these quantities in the SM up to one-loop level are now available [17,18]. The tree-level results are 0.703 for Γ_L/Γ , 0.297 for Γ_-/Γ and $\mathcal{O}(10^{-4})$ for Γ_+/Γ , and the QCD corrections to these predictions are respectively -1.07% , 2.19% and 0.10% , while the electroweak corrections are at the level of a few per mill.

In order to probe the new physics from the future precise measurement of Γ_L/Γ , Γ_-/Γ or Γ_+/Γ , we must know the new physics contributions to these quantities in various models. By now, the one-loop corrections to the total width of $t \rightarrow bW$ in the framework of MSSM have been studied in [19] and the corrections to Γ_L/Γ , Γ_-/Γ or Γ_+/Γ in MSSM were recently studied in Ref. [20], but the similar study in the TC2 model is absent. Studying the corrections on these quantities in the TC2 model is the main goal of this paper.

This paper is organized as follows. In the section II, we first briefly introduce the TC2 model, then we calculate the corrections and discuss our numerical results. The conclusions are given in section III.

II. TOP QUARK DECAYS INTO POLARIZED W-BOSON IN THE TC2 MODEL

A. The TC2 Model

Among various kinds of dynamical electroweak symmetry breaking models, the TC2 model [3,4] is especially attractive since it combines the fancy ideas of technicolor [22] and top quark condensation [5] without conflicting with low energy experimental data. The basic thought of the TC2 model is to introduce two strongly interacting sectors. One sector(topcolor interaction) provides the main part of top quark mass but has the small contribution to EWSB, while the other sector(technicolor interaction) is responsible for the bulk of EWSB and the masses of light fermions. At EWSB scale, this model predicts two groups of scalars corresponding to the technicolor condensates and topcolor condensates, respectively [3–5]. Either of them can be arranged into a $SU(2)$ doublet [23–25], and their roles in TC2 model are quite analogous to the Higgs fields in the model proposed in Ref. [26] which is a special two-Higgs-doublet model in essence. Explicit speaking, the doublet Φ_{TC} which corresponds to the technicolor condensates is mainly responsible for EWSB and light fermion masses, it also contributes a small portion of top quark mass. Because its vacuum expectation value (vev) v_{TC} is near the EWSB scale(v_w), the Yukawa couplings of this doublet to the fermions are small. While the doublet Φ_{TOPC} which corresponds to the topcolor condensates plays a minor role in EWSB and only couples to the third generation quarks, its main task is to generate the large top quark mass. Since the vev of Φ_{TOPC} (denoted as F_t) can not be large(see below), the doublet Φ_{TOPC} can couple strongly to top quark to generate the expected top quark mass.

One distinct feature of this model is that there exist tree level flavor changing couplings for the two scalar fields(Φ_{TC}, Φ_{TOPC}) [26] which is theoretically disfavored. Such defect may be partially alleviated if the mixing angle between two scalar fields, which is a model dependent parameter, satisfies $\tan \alpha = \frac{F_t}{v_{TC}}$ [26]. In this case, only one scalar field has the flavor changing couplings and the rearranged Lagrangian has the following characteristics: one rearranged doublet is fully responsible for EWSB, but with small Yukawa coupling to all fermions; while the other rearranged doublet(denoted as: Φ) has strong Yukawa coupling with the third generation quarks [10]. The Lagrangian relevant to our calculation then can be written as ¹

$$\mathcal{L} = |D_\mu \Phi|^2 - Y_t \frac{\sqrt{v_w^2 - F_t^2}}{v_w} \bar{\Psi}_L \Phi t_R - Y_t \frac{\sqrt{v_w^2 - F_t^2}}{v_w} \bar{t}_R \Phi \Psi_L - m_t \bar{t} t \quad (1)$$

where, $v_w \equiv v/\sqrt{2} \simeq 174$ GeV, $Y_t = \frac{(1-\epsilon)m_t}{F_t}$ is the Yukawa coupling, Ψ_L is the $SU(2)_L$ top-bottom doublet as usual, Φ is the rearranged $SU(2)$ doublet and takes the form

¹The Lagrangian in Ref. [25] corresponds to the case $\tan \alpha = 0$. As far as the process considered in this paper, these two natural choices of $\tan \alpha$ do not make any significant difference in numerical results since in both cases, h_t is top condensates dominant. But our choice of $\tan \alpha$ will make the calculation simplified.

$$\Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}(h_t^0 + i\pi_t^0) \\ \pi_t^- \end{pmatrix} \quad (2)$$

and the covariant derivative is

$$D_\mu = \partial_\mu + i\frac{gY}{2}B_\mu + i\frac{g}{2}\tau_i W_\mu^i \quad (3)$$

with the hypercharge of the doublet is $Y = -1$ and g is g_{weak} . In Eq.(1), the factor $\frac{\sqrt{v_w^2 - F_t^2}}{v_w} = \frac{v_{TC}}{v_w}$ indicates the mixing effect between the two doublets. The physical particles (π_t^0, π_t^-) and h_t^0 in the Φ field are called top-pions and top-Higgs, respectively.

From Eq.(1), one can learn that the TC2 parameters relevant to our discussion are ϵ , F_t and the masses of the top-pions and top-Higgs. Before numerical evaluation, we recapitulate the theoretical and experimental constraints on these parameters.

In the TC2 model, ϵ parameterizes the portion of the extended technicolor contribution to the top quark mass. The bare value of ϵ is generated at the ETC scale, and can obtain a large radiative enhancement from topcolor and $U(1)_{Y_1}$ by a factor of order 10 at the weak scale [3]. This ϵ can induce a nonzero top-pion mass (proportional to $\sqrt{\epsilon}$) [27] which can ameliorate the problem of having dangerously light scalars. Numerical analysis shows that, with reasonable choice of other input parameters, ϵ with order $10^{-2} \sim 10^{-1}$ may induce top-pions as massive as the top quark [3]. Indirect phenomenological constraints on ϵ come from low energy flavor changing processes such as $b \rightarrow s\gamma$ [28]. However, these constraints are very weak. Precise value of ϵ may be obtained by elaborately measuring the coupling strength between top-pions/top-Higgs and top quark at the next linear colliders. From theoretical point of view, ϵ with value from 0.01 to 0.1 is favored. For the mode $t \rightarrow Wb$ considered in this paper, ϵ affects our results via $Y_t = \frac{(1-\epsilon)m_t}{F_t}$, we fix $\epsilon = 0.1$ conservatively in this paper.

Now, we turn to discuss the parameter F_t . The Pagels-Stokar formula [29] gives the expression of F_t in terms of the number of quark color N_c , the top quark mass m_t , and the scale Λ at which the condensation occurs:

$$F_t^2 = \frac{N_c}{16\pi^2} m_t^2 \ln \frac{\Lambda^2}{m_t^2}. \quad (4)$$

From this formula, one can infer that, if $t\bar{t}$ condensation is fully responsible for EWSB, i.e. $F_t \simeq v_w \equiv v/\sqrt{2} = 174$ GeV, then, Λ is about $10^{13} \sim 10^{14}$ GeV. Such a large value is less attractive since one expects new physics scale should not be far higher than the weak scale by the original idea of technicolor theory [22]. On the other hand, if one believes new physics exists at TeV scale, i.e., $\Lambda \sim 1$ TeV, then $F_t \sim 50$ GeV, which means that $t\bar{t}$ condensation cannot be wholly responsible for EWSB and the breaking of electroweak symmetry needs the joint effort of topcolor and other interactions like technicolor. By the way, Eq.(4) should be only understood as a rough guide, and F_t may be somewhat lower or higher. In this paper, we use the value $F_t = 50$ GeV to illustrate the numerical results.

Finally, we focus on the mass bounds of top-pions and top-Higgs. On the theoretical side, some estimates have been done. The mass splitting between the neutral top-pion and the charged top-pions should be small since such splitting comes only from the electroweak interactions [30]. Ref. [3] has estimated the masses of top-pions using quark loop approximation and showed that the masses are allowed to be a few hundred GeV in the reasonable parameter space. Like Eq.(4), such estimates can only be regarded as a rough guide and the precise values of top-pion masses can only be determined by future experiments. The mass of the top-Higgs h_t can be estimated in the Nambu-Jona-Lasinio (NJL) model in the large N_c approximation [31] and is found to be about $2m_t$ [7,24]. This estimates is also rather crude and the mass below the $t\bar{t}$ threshold is quite possible in a variety of scenarios [32]. On the experimental side, the current experiments have restricted the masses of the charged top-pions. For example, the absence of $t \rightarrow \pi_t^+ b$ implies that $m_{\pi_t^+} > 165$ GeV [33] and R_b analysis yields $m_{\pi_t^+} > 220$ GeV [34]. For the masses of neutral top-pion and top-Higgs, the experimental restrictions on them are rather weak. The direct search for the neutral top-pion (top-Higgs) via $pp \rightarrow t\bar{t}\pi_t^0(h_t)$ ² with $\pi_t^0(h_t) \rightarrow b\bar{b}$ has been proved to be hopeless at Tevatron with the top-pion (top-Higgs) heavier than 120 GeV [25]. The single production of $\pi_t^0(h_t)$ at Tevatron with $\pi_t^0(h_t)$ mainly decaying to $t\bar{c}$ may shed some light on detecting the neutral top-pion (top-Higgs) [7], but the potential for the detection is limited by the size of the mixing between top and charm quarks. On the other hand, the detailed background analysis is absent now. Anyhow, these mass bounds will be greatly tightened at the upcoming LHC [8,25]. In our following discussion, we will neglect the mass difference among the top-pions and denote the mass of them as m_{π_t} .

²The production of a top-pion (top-higgs) associated with a single top quark at hadron colliders, $pp \rightarrow t\pi_t^0(h_t)$, has an unobservably small rate since there exists severe cancellation between diagrams contributing to this process [25].

B. Top quark decays into the polarized W boson

Generally speaking, the effective tbW vertex at one loop level gets the contribution from penguin diagrams, fermion self-energy diagrams as well as W boson self-energy diagrams. As far as TC2 model is concerned, the leading part of the first two kinds of diagrams is $\mathcal{O}(Y_t^2)$, while that for the last kind of diagrams is $\mathcal{O}(g^2)$. Considering $Y_t^2 \gg g^2$, we can safely neglect the contribution of W boson self-energy. So, the diagrams we need to calculate are only those shown in Fig.1. The effective tbW can be written as

$$\Gamma^\mu = -i \frac{gV_{tb}}{\sqrt{2}} \{ \gamma^\mu P_L [1 + F_L + \frac{1}{2} \delta Z_b^L + \frac{1}{2} \delta Z_t^L] + \gamma^\mu P_R F_R + P_t^\mu P_L \tilde{F}_L + P_t^\mu P_R \tilde{F}_R \} \quad (5)$$

Here $P_{R,L} \equiv \frac{1}{2}(1 \pm \gamma_5)$ are the chirality projectors. The form factors $F_{L,R}$ and $\tilde{F}_{L,R}$ represent the contributions from the irreducible vertex loops. δZ_b^L and δZ_t^L denote respectively the field renormalization constants for bottom quark and top quark. The explicit expressions are given by (we have neglected bottom quark mass)

$$F_L = \frac{(1-\epsilon)^2}{16\pi^2 V_{tb}} \frac{v_w^2 - F_t^2}{v_w^2} \left(\frac{m_t}{\sqrt{2}F_t} \right)^2 (2C_{24}^e + 2C_{24}^f) \quad (6)$$

$$F_R = 0 \quad (7)$$

$$\tilde{F}_L = 0 \quad (8)$$

$$\begin{aligned} \tilde{F}_R = & \frac{(1-\epsilon)^2}{16\pi^2 V_{tb}} \frac{v_w^2 - F_t^2}{v_w^2} \left(\frac{m_t}{\sqrt{2}F_t} \right)^2 2m_t (C_0^e + 2C_{11}^e + C_{21}^e - C_{12}^e - C_{23}^e \\ & + C_{11}^f + C_{21}^f - C_0^f - C_{11}^f - C_{23}^f - C_{12}^f) \end{aligned} \quad (9)$$

$$\delta Z_t^L = \frac{(1-\epsilon)^2}{16\pi^2} \frac{v_w^2 - F_t^2}{v_w^2} \left(\frac{m_t}{\sqrt{2}F_t} \right)^2 [B_1^b + B_1^c + 2m_t^2(B_1^{a'} + B_1^{b'} + B_1^{c'} + B_0^{b'} - B_0^{c'})] \quad (10)$$

$$\delta Z_b^L = \frac{(1-\epsilon)^2}{16\pi^2} \frac{v_w^2 - F_t^2}{v_w^2} \left(\frac{m_t}{\sqrt{2}F_t} \right)^2 2B_1^d \quad (11)$$

where the functions $B_{0,1}$ and $C_{0,ij}$ are respectively two-point, three-point Feynman integrals defined in [35] and their functional dependences are

$$\begin{aligned} C_{0,ij}^e &= C_{0,ij}(-p_t, p_w, m_t, m_{\pi_t}, m_{\pi_t}), \\ C_{0,ij}^f &= C_{0,ij}(-p_t, p_w, m_t, m_{h_t}, m_{\pi_t}), \\ B_{0,1}^a &= B_{0,1}(-p_t, m_b, m_{\pi_t}), \\ B_{0,1}^b &= B_{0,1}(-p_t, m_t, m_{\pi_t}), \\ B_{0,1}^c &= B_{0,1}(-p_t, m_t, m_{h_t}), \\ B_{0,1}^d &= B_{0,1}(-p_b, m_t, m_{\pi_t}), \end{aligned}$$

respectively, and $B_{0,1}'$ denotes $\partial B_{0,1}/\partial p^2$.

The rate of the top quark decaying into the polarized W -boson can be obtained either by helicity amplitude method [36] or by the project technique introduced in Ref. [17,18]. Their expressions are given by

$$\Gamma_L = \frac{g^2 m_t |V_{tb}|^2}{64\pi} \frac{(1-x^2)^2}{x^2} \left\{ 1 + \text{Re}(\delta Z_b^L + \delta Z_t^L + 2F_L) + \text{Re}(\tilde{F}_R) m_t (1-x^2) \right\}, \quad (12)$$

$$\Gamma_- = \frac{g^2 m_t |V_{tb}|^2}{32\pi} (1-x^2)^2 \left\{ 1 + \text{Re}(\delta Z_b^L + \delta Z_t^L + 2F_L) \right\}, \quad (13)$$

where Γ_L (Γ_-) denotes the rate of the top quark decaying into the longitudinal (transverse-minus) W -boson and $x = M_W/m_t$. In deriving Eqs.(12,13), we have neglected the b -quark mass for simplicity which will produce an uncertainty of several per mille on $\Gamma_{L,-}$. Another consequence of neglecting m_b is $\Gamma_+ = 0$ due to angular momentum conservation [17]. Then, the total decay rate of $t \rightarrow bW$ is obtained by $\Gamma = \Gamma_L + \Gamma_-$. For convenience, we define the ratios

$$\hat{\Gamma}_{L,-} = \Gamma_{L,-}/\Gamma, \quad (14)$$

which can be measured in experiments. We present the relative TC2 corrections as: $\delta\hat{\Gamma}_{L,-}/\hat{\Gamma}_{L,-}^0$ with $\delta\hat{\Gamma}_{L,-}$ denoting the TC2 corrections and $\hat{\Gamma}_{L,-}^0$ denoting the SM predictions. In our numerical evaluation, we fixed $m_t = 178$ GeV [37], $m_b = 0$, $M_W = 80.451$ GeV and $g_{weak} = 0.654$, and vary m_{h_t}, m_{π_t} in experimentally allowed region.

The Fig.2 are the plots of the relative TC2 correction to the decay width $\Gamma(t \rightarrow Wb)$. One distinctive feature of such correction is that, for fixed m_{h_t} , after the deviation from the SM predictions reaches its minimum at a certain value of m_{π_t} , the relative correction increases monotonously. This indicates that there are cancellations among different diagrams³. Another feature is that the correction is negative in all allowed parameter space. Noticing the fact that QCD correction to $\Gamma(t \rightarrow Wb)$ is -8.54% [17,18], one can conclude that the TC2 correction can enlarge the quantum effects. From Fig.2, one can see that, for the light top-Higgs, the relative correction can reach -8% . Comparing with the correction in the popular MSSM model where the SUSY-QCD correction and the SUSY-EW correction tend to cancel each other [20], we find that the TC2 correction is larger than either of SUSY-QCD and SUSY-EW correction and TC2 correction might be detectable at the future high energy colliders [21,2]. In Fig.2, we have fixed F_t as 50 GeV. To get the correction for any other choice of F_t , we just multiply the results of Fig.2 by a factor $\frac{v_w^2 - F_t^2}{v_w^2 - 50^2} \frac{50^2}{F_t^2}$ (For example, multiplying a factor 1.6 for $F_t = 40$ GeV and 0.35 for $F_t = 80$ GeV).

In Fig.3 and Fig.4, we show the relative TC2 correction to $\hat{\Gamma}_L$ and $\hat{\Gamma}_-$ as a function of m_{π_t} . One can see that the correction is below 1%, smaller than the corresponding QCD correction [17,18] but larger than the corresponding MSSM corrections [20]. Comparing with the results in Fig.2, we can see that the correction to $\hat{\Gamma}_{L,-}$ is smaller than that to total decay width. This is due to the cancellation between the correction to $\Gamma_{L,-}$ and to Γ in eq.(14). For example, when we take $m_{h_t} = 120$ GeV and $m_{\pi_t} = 750$ GeV, the relative correction to the total width $\delta\Gamma/\Gamma^0$ is about -8% ($\delta\Gamma_L/\Gamma^0 = -5.6\%$ and $\delta\Gamma_-/\Gamma^0 = -2.4\%$, respectively), but for the same values of m_{h_t} and m_{π_t} , $\delta\hat{\Gamma}_L/\hat{\Gamma}_L^0 = 0.13\%$ and $\delta\hat{\Gamma}_-/\hat{\Gamma}_-^0 = -0.34\%$. Comparing with the experimental data, we can conclude that the theoretical prediction of $\hat{\Gamma}_{L,-}$ including the TC2 correction should be within the experimentally allowed region.

III. CONCLUSION

In this paper, we study the TC2 correction to the mode $t \rightarrow Wb$. We find that, due to the cancellations among different diagrams, the TC2 correction to the width $\Gamma(t \rightarrow bW)$ is generally several percent in the allowed parameter region. The maximum value of the relative correction can reach 8% which is larger than that of minimal supersymmetric model and comparable with the QCD correction. Such TC2 correction should be observable at future high energy colliders. We also study the TC2 correction to the branching ratio of top quark decaying into different polarized W boson states and find the relative TC2 correction is below 1%.

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³If different diagram contributions are constructive, then for fix m_{h_t} , the deviation will decrease monotonously with increasing m_{π_t} to approach a constant.

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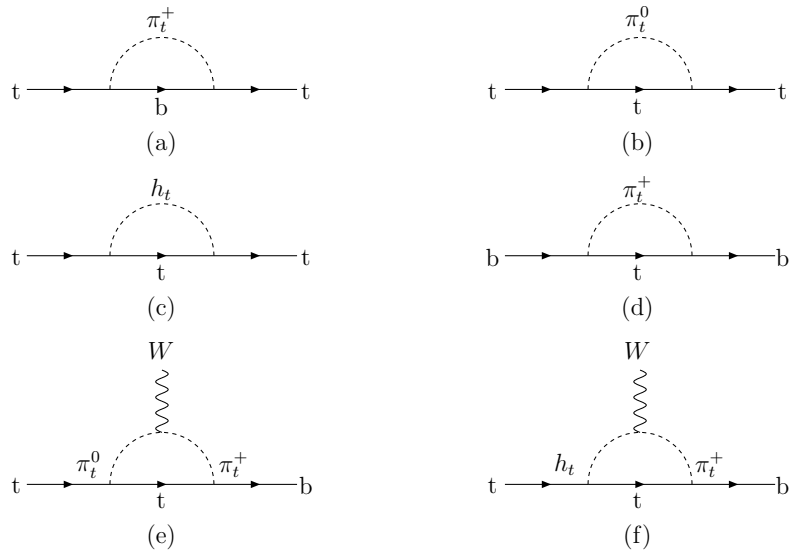


FIG. 1. The Feynman diagrams for TC2 correction to $t \rightarrow bW$.

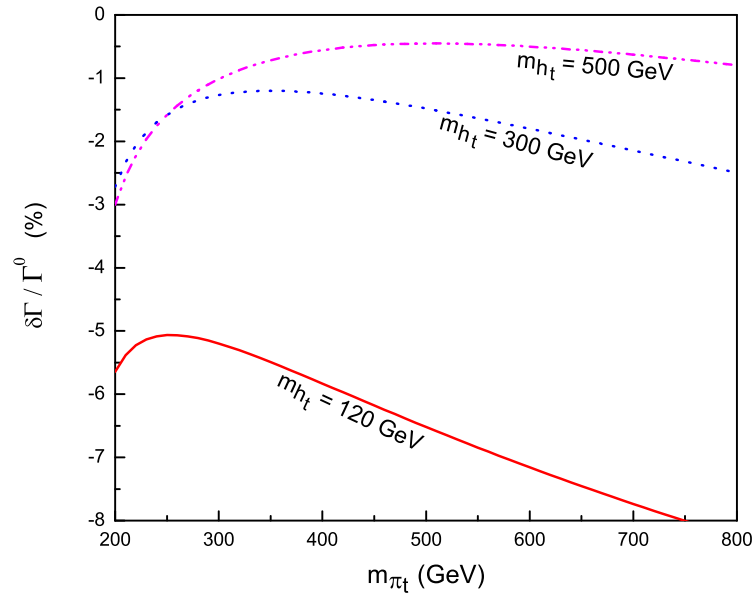


FIG. 2. The TC2 correction to the width of $\Gamma(t \rightarrow bW)$ versus m_{π_t} for different m_{h_t} .

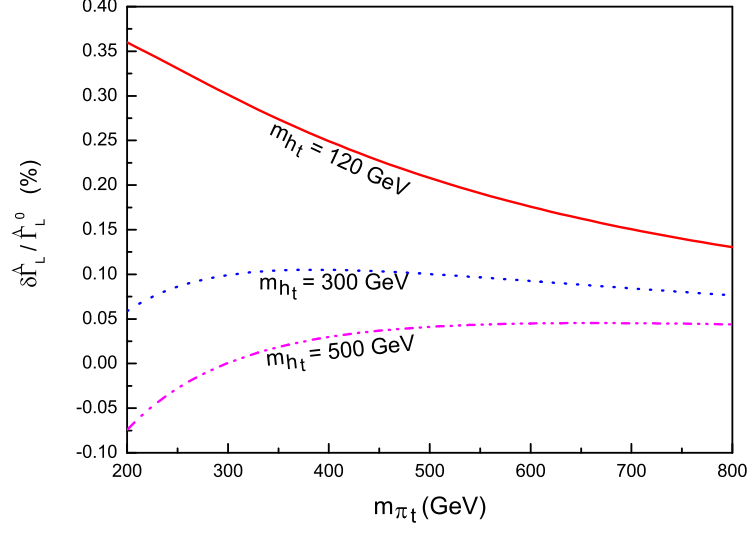


FIG. 3. The relative TC2 correction to $\hat{\Gamma}_L$ as a function of m_{π_t} .

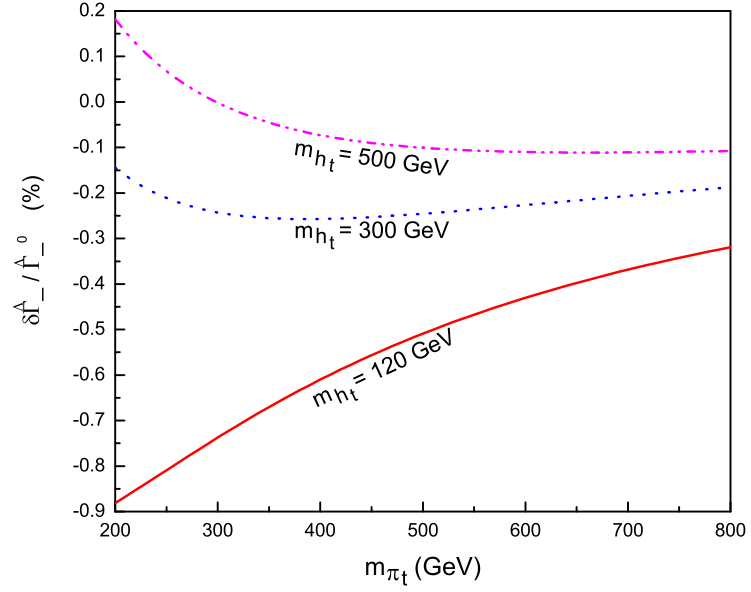


FIG. 4. The relative TC2 correction to $\hat{\Gamma}_-$ as a function of m_{π_t} .